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A STUDY OF THE "PENINSULA METHOD" FOR THE CONTROLLED ARTIFICIAL GENERATION OF ULF WAVES IN THE IONOSPHERE AND MAGNETOSPHERE

by

A. C. Fraser-Smith,
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D. M. Bubenik

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This report presents the results of an investigation of a proposed method for the controlled artificial generation of ultra-low-frequency (ULF) hydromagnetic waves, primarily of class Pc 1 (0.2 to 5 Hz), in the ionosphere and magnetosphere. The basis of this method, which is called the "peninsula method" (a second possible method, the "VLF method," is discussed in a companion report), is the passage of a ULF-modulated electric current around a relatively nonconducting peninsula in the sea or in a large saline lake to form a ULF current loop that produces a ULF magnetic field in the lower

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20 ABSTRACT (Continued)

ionosphere. Provided the amplitude of the ULF magnetic field fluctuations is sufficiently large, i.e., provided the maximum magnetic moment of the peninsula current loop is greater than about 10^{13} Am^2, it is predicted theoretically that ULF hydromagnetic waves can be generated in a disturbed region of the lower ionosphere above the peninsula. These waves can then propagate away to large distances in the ionosphere and magnetosphere.

The peninsula method is a version of a particular class of ULF wave generation methods based on the use of large ground-based ULF current systems. Compared with other possible methods of generation, these methods appear to have the advantage of reliability and versatility. However, both the construction costs and the power requirements for these systems are large. The peninsula method is particularly attractive because it would minimize these latter disadvantages.

Experiments conducted in 1975 and 1976 with a small peninsula on Chappaquiddick Island, Massachusetts, show that the sea (or salt) water surrounding a peninsula can indeed function as a conducting loop and that this loop can be used to produce ULF magnetic fields above the peninsula. A modeling study based on the results of these experiments indicates that the peninsula method is very efficient: the magnetic field produced at E region height by an electric current flowing through the sea water surrounding the peninsula can be up to 49 times larger than the magnetic field that would be generated by the same current flowing through a wire loop laid along the shoreline of the peninsula. In addition, because of the low resistance of the sea water path, the power required to drive the current through the sea water around the peninsula can be more than an order of magnitude smaller than the power required to drive the same current through the wire loop. Thus the magnetic field produced per unit of input power is substantially higher for the peninsula current loop than it is for a large horizontal wire loop on the ground. The estimated cost of constructing a peninsula ULF generator is found to be over an order of magnitude less than the estimated cost of a horizontal wire loop system of similar capability. We conclude that the peninsula method of ULF wave generation is feasible and that further experiments, particularly a full-scale ULF generation experiment, are desirable.

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ABSTRACT

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ACKNOWLEDGMENTS

We wish to thank Mr. and Mrs. George F. Hodder and the late Mr. and Mrs. Eric Hartell for permission to set up our equipment on and adjacent to their North Neck properties on Chappaquiddick Island. We also gratefully acknowledge the assistance of Houghton Lewis during the 1975 and 1976 experiments, and the contribution of James L. Buxton, who helped design and who constructed all the specialized equipment used during the experiments.

Special thanks are due to Lieutenant James L. Nupp and his crew on the Patrol Wing Five aircraft from the U.S. Naval Air Station at Brunswick, Maine, who made the airborne magnetometer measurements during the 1976 experiments. The help given by Lieutenant Donald L. Christiansen with the arrangements is also appreciated.

Finally, we thank our colleagues Belinda J. Lipa and Kenneth J. Harker for their theoretical studies of (1) the magnetic field fluctuations that were likely to be produced in the lower ionosphere by the peninsula "antenna" (BJL), and (2) the ULF waves that could be generated in the ionosphere by ground-based electric or magnetic dipoles (KJH). These studies, together with the work of Carl and Phyllis Greifinger at RDA Inc. on ULF wave generation with ground-based dipoles, provided a strong theoretical basis for our experiments.

Support for this work was provided by the Defense Advanced Research Projects Agency (ARPA Order No. 1733, A10 and A11) through the Office of Naval Research Contract No. N00014-75-C-1095.

Note: In this report we use the abbreviation ULF (ultra-low-frequencies) for frequencies less than 5 Hz. Pc 1 geomagnetic pulsations are observed in the upper part of this frequency range (0.2 to 5 Hz). ELF (extremely-low-frequencies) is used to designate frequencies in the range 5 Hz to 3 kHz, and VLF (very-low-frequencies) is used for frequencies in the range 3 to 30 kHz.

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ILLUSTRATIONS

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I. INTRODUCTION

In 1972, Fraser-Smith et al. (1972) and Greifinger (1972) proposed that the ULF-modulated magnetic field from a large ground-based current loop driven by a ULF oscillator would disturb the lower ionosphere and produce ULF hydromagnetic waves that could propagate away to large distances in the ionosphere and magnetosphere. This proposal was soon followed by several other suggestions for possible ULF signal generators. The suggestions included a large horizontal electric dipole antenna (Greifinger and Greifinger, 1974; Harker, 1975), a large vertical electric dipole antenna (Harker, 1975), direct modification of currents in the lower ionosphere (Davis and Willis, 1974), and the use of VLF radio transmissions into the magnetosphere (Harker et al., 1974 a, b; Bell, 1976). The ground-based current loop antenna and horizontal electric dipole antenna methods appear to have the advantage of reliability and versatility, but, to generate observable pulsations, the dipole moments of the antennas must be large, i.e., the antennas must be physically large and their power requirement is many megawatts. It was for this reason that the peninsula method for the generation of ULF signals was proposed.

The peninsula method is a version of the ground-based current loop method for ULF signal generation, in which a ULF-modulated electric current is passed around a relatively nonconducting peninsula in the sea or in a large saline lake. By using the sea water as a conductor it is no longer necessary to construct a large wire loop, with a consequent large saving in construction costs. Furthermore, the land requirements

are greatly reduced, and, because of the large volume of sea water involved and the subsequent low resistance of the sea water circuit, the power required to drive a large loop current is comparatively small.

The essential condition for ULF hydromagnetic wave generation in the ionosphere by a large ground-based current loop is that the loop should have a large peak magnetic moment. To illustrate, Fraser-Smith et al. (1972) and Greifinger (1972) deduced that loops with peak moments in the range 10^{13} to 10^{14} Am^2 would be necessary if significant hydromagnetic wave amplitudes were to be produced in the ionosphere, and the work of Harker (1975) supported this conclusion. To produce a moment in this range, a single- or multi-turn loop with a radius of the order of 50 km and a current of the order of 3000 A is required. The power required to drive this current through the loop depends on the resistance and therefore on the composition and gauge of the wire: for moderately heavy (2000 mcm) aluminum wire the power requirement for a single-turn loop can be as great as 100 MW. (Note that in this case, for a single-turn loop, the magnetic field produced at an altitude of 100 km is approximately 5γ.) There is no doubt, therefore, that the peninsula required for ULF wave generation should have as large an area as possible.

Lipa et al. (1975) analyzed a peninsula model consisting of a circular island connected to the shore of a large circular sea by a narrow neck. All the sea boundaries, including the sea floor, were assumed to be insulating, and the physical dimensions chosen for this model were: island radius, 10 km; sea radius, 100 km; neck length,

100 m; sea depth, 50 m. It was assumed that an electric current of 3000 A was driven around the island by a ULF potential difference between two electrodes located on either side and completely covering the neck. The amplitude of the magnetic field generated directly over the island by this model peninsula system was approximately 4γ at an altitude of 100 km, and the power required to drive the 3000 A current was 2.4 MW.

Comparing the model peninsula system with the single-turn, 50 km radius loop, we see that they both produce comparable magnetic field amplitudes at an altitude of 100 km if the currents are the same. However, the power required to drive the current around the peninsula is between 10 and 100 times smaller than the power required to drive the same current through the wire loop.

Although the work of Lipa et al. (1975) suggests that the generation of ULF hydromagnetic waves in the ionosphere by the peninsula method has several important advantages over the basic wire loop method, there are a number of assumptions in the peninsula method theory that must be largely satisfied in practice if the method is to be effective. One of the most important properties required for an actual peninsula is a high electrical resistance across its neck. If this resistance is low, current will leak through the neck instead of passing around the peninsula, and the overall loop magnetic moment will be correspondingly reduced.

Most of the assumptions made by Lipa et al. (1975) are difficult to assess theoretically. Thus, to provide practical data, experiments were conducted during the summers of 1975 and 1976 on a small peninsula

on Chappaquiddick Island, Massachusetts. The peninsula chosen, called North Neck, projects into the almost totally enclosed Cape Poge Bay. It does not rise very high above normal sea level, and it is largely composed of sand and is marshy in places; nevertheless, the peninsula contains fresh ground water, and the electrical resistance across it proved to be high enough to allow useful experiments to be conducted. The results of these experiments and of the modelling effort that resulted from them are described in the following chapters.

This report is one of a pair whose common topic is the controlled artificial generation of ULF geomagnetic pulsations. The second report presents the results of a study of the "VLF method" of generation, i.e., the use of pulsed VLF transmissions into the magnetosphere from a large ground-based VLF transmitter to produce ULF hydromagnetic waves in the ionosphere and magnetosphere.

II. ULF RECORDING EXPERIMENT, 1975

As a first test of the peninsula generation concept, it was decided in 1975 to attempt an exploratory passive ULF recording experiment using the sea water around a peninsula as a receiving loop. There were two reasons for attempting this experiment as a first test of the generation concept. First, it would require little experimental equipment, and yet if successful it would provide strong evidence for the existence of a usable conducting path around the peninsula. Second, the experiment would provide an introduction to the difficulties that were likely to be encountered during a generation experiment.

Figure 1 shows a schematic representation of the experiment: a ULF receiver is connected to two electrodes on either side of the peninsula, and ULF signals are recorded by using the sea surrounding the peninsula as a distributed loop antenna. The figure emphasizes two desirable features for the peninsula: (1) a narrow, nonconducting neck, to minimize the length of wire required to connect the electrodes to the ULF receiver, and (2) a large peninsula area beyond the neck, to ensure a large minimum receiving area for the ULF "antenna."

As noted in Chapter 1, the peninsula chosen for the experiment was on Chappaquiddick Island, Massachusetts. Figure 2 shows a map of the actual peninsula and surrounding area. Having the peninsula within an almost totally enclosed bay was particularly advantageous, since the experimental configuration then closely resembled the one studied theoretically by Lipa et al. (1975), and the existence of well-defined boundaries to the sea water enclosing the peninsula greatly simplified

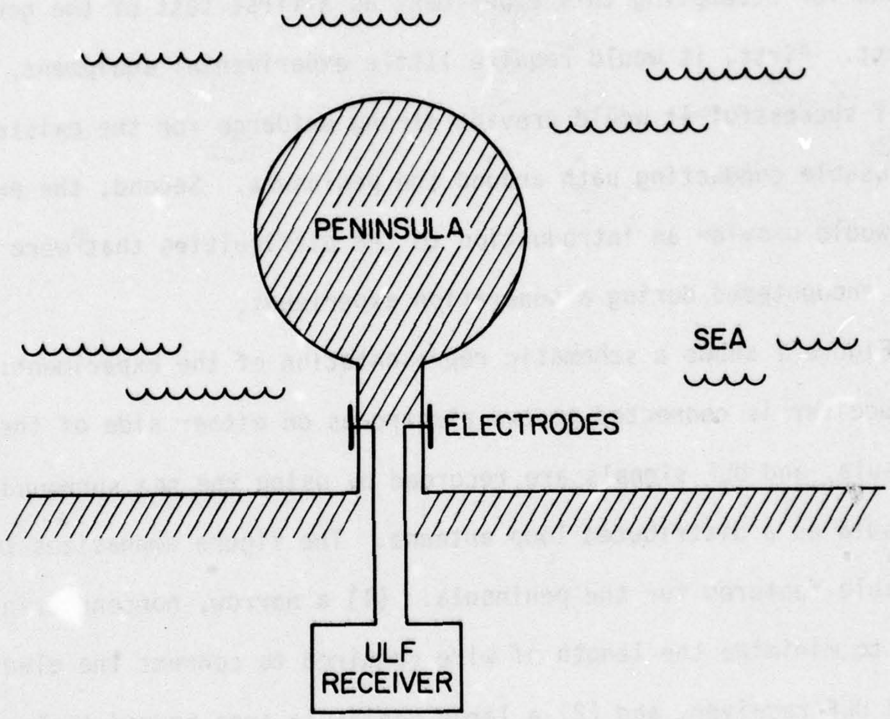

Figure 1. Schematic geometry of the peninsula ULF receiving experiment, 1975.

Figure 2. Map of Chappaquiddick Island, Massachusetts. The experiment was conducted on North Neck, which projects into Cape Poge Bay (upper right), and the location of the electrodes on either side of the Neck is superimposed on the map. To indicate scale, the longitude lines are 2.8 km apart. The compass rose points to geomagnetic north.

later calculations of the magnetic fields produced by electric currents flowing in the sea water.

The equipment for the experiment was set up during August 1975. In its original form it consisted of two copper electrodes, which were constructed of thin copper sheet about 0.45 m square, connected by shielded cables to the input of an electronics package consisting of a ULF differential amplifier, a timer, a calibrator, and a low-pass filter. The output of the electronics package was recorded with both a monitoring paper chart recorder and with a slow-speed analog magnetic tape recorder. The location of the electrodes and cable is superimposed on the map of the peninsula shown in Figure 2. One electrode was immersed in the relatively deep water of Cape Poge Gut and was connected to the electronics package by approximately 100 m of cable; the other electrode was immersed in the relatively shallow water of Cape Poge Bay and was connected to the electronics package by approximately 200 m of cable. Shielded cable was required to reduce the input of sferic noise. The resistance of the cable-electrode-sea water-electrode-cable circuit, as seen by the electronics package, was approximately 12 Ω. About 10 Ω of this resistance was due to the cables, i.e., the resistance between the two electrodes was roughly 2 Ω.

The amplifier had a bandpass of 0.1 to 15 Hz, a voltage gain that was adjustable in the range 500 to 500,000, and an input impedance of 2 MΩ. For the first 30 seconds of each hour, the timer automatically turned on the calibrator, which applied a 1 Hz square wave current source to the input terminal of the amplifier. In normal operation the output of the amplifier was passed through the filter before it was

recorded. The filter was used to reduce the strong power line signals that were picked up; it had a voltage gain of two at frequencies below 15 Hz (the 3 db point of the filter occurred at 20 Hz), and it attenuated 60 Hz signals by more than 60 db.

During preliminary tests of the ULF recorder, it was found that instabilities were caused by dc potential differences in the range 0.01-0.03 V that occurred between the two electrodes. These potential differences were removed by the insertion of a single-stage balanced RC high-pass filter ($R = 75\ k\Omega$, $C = 0.8\ \mu F$) between the electrodes inputs and the amplifier. With this modification, and with the amplifier gain setting that was selected for the experiment, the overall system voltage gain measured from the electrodes to the recorder input was 200 at a frequency of 1 Hz.

Recordings of ULF geomagnetic pulsation activity were made using the peninsula "antenna" for each night in the interval 26 August through 5 September 1975. Well-defined Pc 1 pulsation events of comparatively short duration (15-30 minutes) were recorded on a number of these nights, thus demonstrating the validity of the peninsula ULF "antenna" concept. Toward the end of the recording interval, a particularly long-lasting and large-amplitude Pc 1 pulsation event was observed. A spectrogram of this event, as recorded at Chappaquiddick Island (CH), is displayed in Figure 3, together with spectrograms of the same event as seen at Roberval, Quebec (RO) and at Stanford, California (ST). Figure 4 shows the locations of the Roberval and Stanford recording sites relative to Chappaquiddick.

The Pc 1 pulsation activity at Roberval and at Stanford was recorded with identical North-South solenoid antennas, and thus it is the time variation of the North-South horizontal component of the geomagnetic field at these two sites that is displayed in Figure 3. The Chappaquiddick data, on the other hand, probably represent the time variation of the vertical component of the geomagnetic field. The amplitude of the vertical magnetic field fluctuations that occur during a Pc 1 pulsation event is usually considerably smaller than the amplitude of the horizontal magnetic field fluctuations. Thus, the strength and duration of the Chappaquiddick Pc 1 pulsation event in Figure 3 suggests that the peninsula "antenna" was highly sensitive.

In conclusion, the passive ULF recording experiment of August-September 1975 demonstrated that the sea water conducting path around a peninsula could be used as part of a ULF "antenna," with the implication that the conducting path could also be used as the principal component of a current loop capable of generating ULF magnetic fields. As a result of this encouraging result, planning went ahead for an exploratory active experiment using the North Neck peninsula during the summer of 1976.

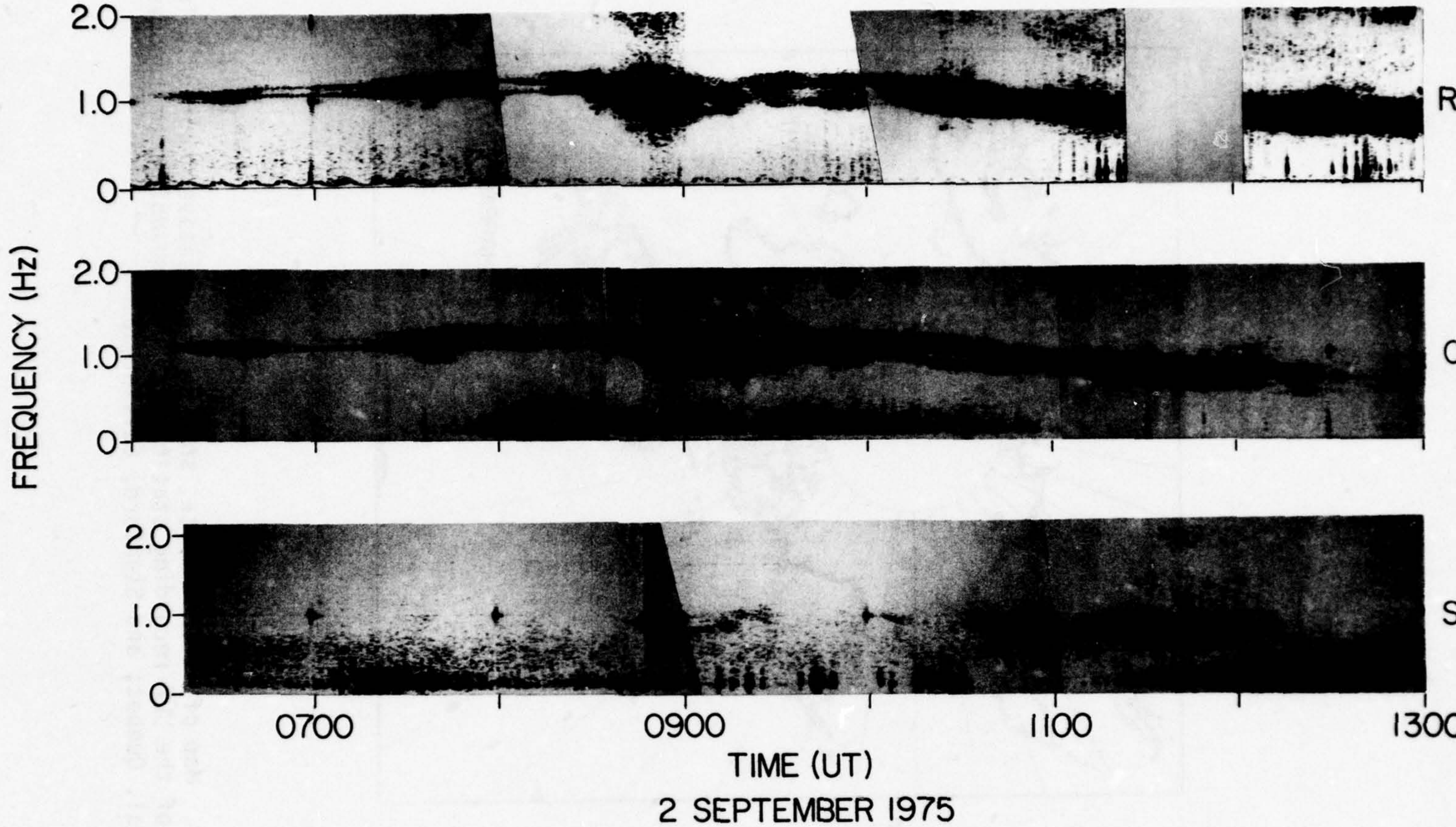

Figure 3. Spectrograms of a long-lasting Pc 1 geomagnetic pulsation event, as recorded at Roberval, Quebec (RO), Chappaquiddick Island, Massachusetts (CH), and at Stanford, California (ST). The recording at Chappaquiddick Island was made with a peninsula "antenna;" the other recordings were made with conventional ULF solenoid antennas. A power failure caused the blank interval in the Roberval record.

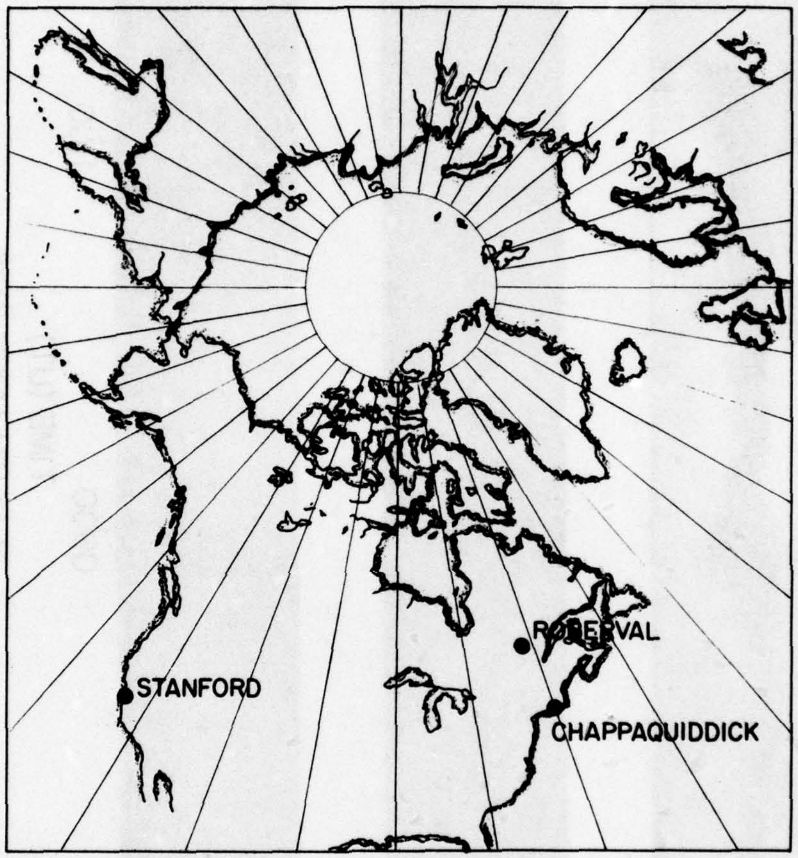

Figure 4. Map of North America, showing the relative geographic locations of the ULF recording stations at Chappaquiddick, Massachusetts; Roberval, Quebec; and Stanford, California.

III. ULF MAGNETIC FIELD GENERATION EXPERIMENT, 1976

The object of this experiment was to use the peninsula "antenna" to produce a ULF magnetic field and, by suitable measurement and calculation, to establish the experimental conditions for a full-scale ULF generation experiment. Once again, it was an exploratory experiment. However, unlike the ULF recording experiment in 1975, whose object was to verify the peninsula "antenna" concept, the 1976 experiment was intended to verify the advantages of the peninsula "antenna" for ULF generation as compared with a large wire loop laid on the ground.

The experiment took place during the summer of 1976, and once again it made use of the North Neck peninsula on Chappaquiddick Island. Electrodes were installed at the same location as during 1975, but they were of different design from those used the previous year. They were constructed of 2 m lengths of standard galvanized iron pipe (outer diameter ≈ 2.5 cm), and assembly was in the form of the letter H, with the long members ≈ 4 m long and separated by a cross-bar of length ≈ 2 m. The electrodes were connected to the ULF current source by #4 insulated aluminum wire (wire diameter 0.518 cm). The distance between the electrode in the Gut and the current source located on North Neck was about 40 m, and the distance between the electrode on the other side of the peninsula and the current source was about 140 m. Thus the electrodes were about 180 m apart. Connection of the wire to the electrodes was made by means of worm-gear hose clamps at the center of the cross-bar, and the connection was taped and sealed before the electrodes were immersed in the sea water. The object of the large electrodes and thick aluminum wire was to minimize the resistance of

the wire-electrode-sea water-electrode-wire circuit. This object was achieved, because the measured resistance of the circuit was approximately 0.4 Ω, compared with approximately 12 Ω the previous year.

Power for the experiment was provided by two 12 V automobile batteries connected in series. The current flow from these batteries was checked both before and after the tests, and it was found to be the same in all cases. The ULF current controller was designed and constructed in a joint effort with SRI International. Its specifications stated that it should deliver 100 A into a 0.1 Ω load for frequencies in the range 0.5 Hz through 5 Hz when connected to the 24 V automobile battery power supply. In addition, it was specified that the keying cycle should be an on-off cycle of seven stepwise approximated sine waves followed by an off period equivalent to one period in duration. This keying made it possible to determine the phase of the received signal. The unit delivered used four automobile starter relays in a bridge circuit to produce the pseudo sine wave alternating current, and it matched or exceeded all its specifications. When connected to the electrodes through the aluminum wires, it delivered a maximum of 60 A into the 0.4 Ω load, and its frequency was adjustable from less than 0.5 Hz up to nearly 12 Hz.

The ULF generation experiment, using the ULF current source and electrodes just described, had three components as follows. First, ground measurements were made of the magnetic field produced on the peninsula and its vicinity. Second, the currents produced in the sea water were measured using a three-axis current probe. Third, with the cooperation of the Office of Naval Research and Patrol Wing Five

personnel at the U.S. Naval Air Station at Brunswick, Maine, measurements of the magnetic field produced by the ULF current source and peninsula "antenna" were made in the air above the peninsula using the MAD magnetometer on a P-3C aircraft.

A two-axis fluxgate magnetometer built by Superconducting Technology Inc. (Model F212) was used for the ground measurements of magnetic field. This instrument had a flat frequency response from dc up to frequencies well above the ULF range, and its noise level was approximately 1-2 γ in the 0.2-5 Hz band. Preliminary calculations indicated that a magnetometer with this sensitivity could make useful measurements of the ULF magnetic fields produced along the peninsula during the generation experiment, and this proved to be the case in practice.

A specially-constructed three-axis current probe/preamplifier system was used to measure the ULF currents in the sea water surrounding North Neck. This system was constructed by SRI International, and it delivered signal voltages proportional to the three orthogonal components of current at a single location in the sea water. The probe had three pairs of contacts, and the spacing between the contacts was 0.5 m. Each contact pair fed a preamplifier with a voltage gain of 100 and a bandpass of 0.5 to 5 Hz (3 db points), and the outputs from the preamplifiers were recorded sequentially on a Gulton portable chart recorder.

All three components of the experiment provided useful data. The magnetic field measurements along the peninsula were largely dominated by the magnetic field from the two electrode feed wires, which together could be considered to form a single straight segment of wire, of

length 180 m, crossing the peninsula at a right angle. Thus, the magnetic field close to the wire was largely vertical, and it varied inversely with distance from the wire. The amplitudes of the calculated fields at various locations were always higher than the actual measured values. For example, the amplitude of the vertical component of the field measured at a perpendicular distance of 30.5 m from the wire was 310 γ (for a maximum current of 60 A) compared with a calculated value of 393 γ. The difference of approximately 20% between the calculated and measured values is attributed to current flow through the peninsula. Since the magnetic field generated by the feed wires was directly proportional to the current flow, it appears that about 20% of the current leaving one electrode flowed directly back through the peninsula to the other electrode.

The principal result of the current probe measurements in the sea water around the electrodes was the determination that the current close to the electrodes flowed predominantly radially away from the electrodes. Because of current flow through the peninsula, the component of the radial flow directly inward toward the peninsula was to be expected. Also anticipated, and actually observed, was a component of current flow roughly parallel to the peninsula and directed toward the seaward end. The component of the current flow directed away from the peninsula was less certainly expected, but its existence was predicted theoretically for the ideal peninsula model considered by Lipa et al. (1975). Current flow directed away from the peninsula is desirable for ULF generation, because it feeds current loops of large area in the sea and therefore ultimately leads to a large overall

magnetic moment for the peninsula loop "antenna." Thus the current probe measurements close to the electrodes were consistent with, and provided support for, the existence of a sea water current loop around the peninsula.

There was considerable background noise in the current probe measurements caused by motion of the boat used in the experiment and by the related motion of the probe in the water. Because of this background noise, it was not possible to make measurements of the current flow at distances of more than about 160 m from the electrodes. Thus, it was not possible to investigate the flow of current around the end of the peninsula or at other large distances from the electrodes.

The total field magnetometer on the P-3C Orion detected the magnetic field from the currents flowing around the peninsula on all of its eight passes, which were made at altitudes in the range 160 to 320 m. The sensitivity of the recording system was reduced after each pass, and even on the last pass, with minimum sensitivity, the peninsula current loop produced off-scale readings. The magnetic "anomaly" was reported to resemble a large merchant ship seen at low altitude. These measurements demonstrated that the peninsula current loop could indeed generate large magnetic fields above the peninsula with a comparatively modest power supply--in this case two automobile batteries.

It had become clear during the 1976 series of ULF generation experiments that the concept of generating ULF magnetic fields by passing a ULF current through the sea water around a peninsula was feasible. It still remained to demonstrate the great gain in magnetic field strength produced in the ionosphere by a peninsula current loop

compared with a wire current loop of the same dimensions as the peninsula. For this reason, we initiated a theoretical program where we modeled the North Neck peninsula and surrounding Cape Poge Bay and, in a series of computer calculations, determined the magnetic field that could be produced in the E region of the ionosphere.

IV. MODEL CALCULATIONS

The primary object of this theoretical program was to derive the magnetic fields produced above the sea, and in particular in the lower ionosphere, by the ULF electric currents flowing around the North Neck peninsula. It was hoped that the method used to derive the magnetic fields would be sufficiently general to cover other peninsula/sea water configurations that might be used in a full scale ULF generation experiment. The method now to be described satisfied this requirement.

The theoretical modeling program proceeded along the following steps: (1) A model of Cape Poge Bay, the North Neck peninsula, and the electrodes was constructed in a form suitable for computer computation. (2) The potential distribution in the water due to unit potential difference across the electrodes was computed by using a relaxation method of solution for Laplace's equation. (3) The electric currents arising from this potential distribution were determined. (4) The magnetic fields produced by these currents above the sea were computed at selected points.

The model used in the electric current calculations is shown in Figure 5. The shore of the bay is represented in an idealized fashion by straight line segments which intersect at angles which are integer multiples of 45°. The inlet to the actual bay, just above the peninsula, is closed, as are other minor pools and inlets around the bay. It was assumed (and later confirmed by the calculations) that the electrical current flow across these boundaries would be negligible. The bay was assumed to be uniformly 1 meter deep; because of the linearity of the problem, other depths could be taken into account by simple scaling.

The electrodes were modeled as points at A and B, and for simplicity, the bay shore and bottom were assumed to be nonconducting.

The first major task was to compute the two-dimensional electric current density $\overline{J}(x,y)$ in the water. In a watery medium of conductivity σ, we have

$$\overline{J}(x,y) = \sigma\overline{E}(x,y) \ , \qquad (1)$$

and

$$\overline{J}(x,y) = -\sigma\nabla\phi(x,y) \ , \qquad (2)$$

where ϕ is the electrical potential in the medium. Since the medium is charge free, ϕ can be found by solving Laplace's equation

$$\nabla^2\phi(x,y) = 0 \ ,$$

subject to the appropriate boundary conditions. Because the shore is nonconducting, at the boundaries $\overline{J}(x,y)$ must flow parallel to the boundary. Thus we have

$$\overline{J}_\perp(x,y)_{\text{boundary}} \equiv 0 \ , \qquad (3)$$

and thus

$$-\sigma(\nabla\phi).\overline{n} \equiv 0 \ , \qquad (4)$$

where $\overline{n}$ is the unit vector normal to the boundary at each point. Given the potential at each electrode ($\phi_A = -0.5$ V, $\phi_B = +0.5$ V), it was then necessary to solve Laplace's equation with mixed Neumann-Dirichlet boundary conditions. This was done using a standard finite difference

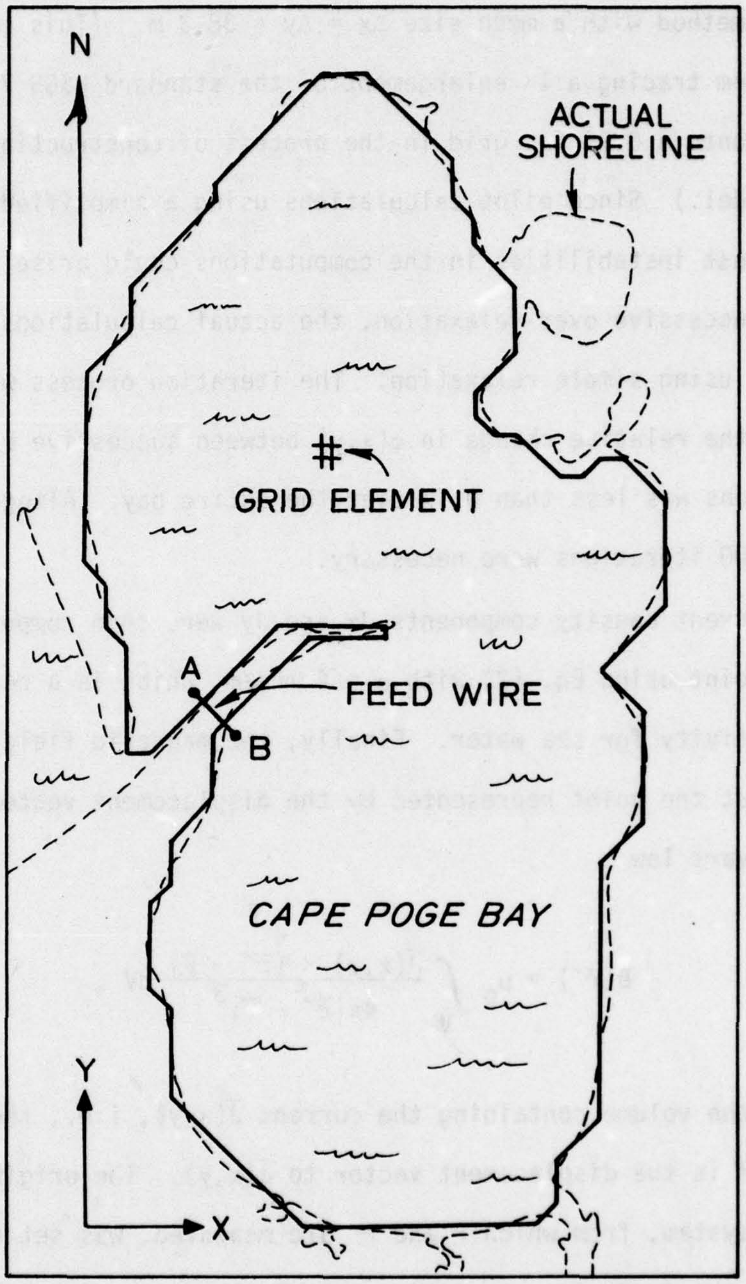

Figure 5. Model of Cape Poge Bay, Chappaquiddick Island. The actual shoreline is shown by the lightweight dashed line; the straight line segment approximation is shown by the heavy solid line. The electrodes were at points A(-) and B(+). An element of the computational grid (drawn to scale) is shown in the upper part of the figure.

relaxation method with a mesh size $\Delta x = \Delta y = 38.3$ m. (This mesh size resulted from tracing a 4× enlargement of the standard USGS 7.5 ft map of the bay onto a 0.25 in. grid in the process of constructing the computer model.) Since pilot calculations using a simplified geometry indicated that instabilities in the computations could arise using the method of successive over-relaxation, the actual calculations were carried out using simple relaxation. The iteration process was terminated when the relative change in $\phi(x,y)$ between successive blocks of 250 iterations was less than 0.1% over the entire bay. Altogether, a total of 6000 iterations were necessary.

The current density components Jx and Jy were then computed at each mesh point using Eq. (2) with $\sigma = 4$ mho/m, which is a representative conductivity for sea water. Finally, the magnetic field $\overline{B}(\overline{r})$ was calculated at the point represented by the displacement vector $\overline{r}'$ from the Biot-Savart law

$$\overline{B}(\overline{r}') = \mu_o \int_V \frac{\overline{J}(x,y) \times (\overline{r}' - \overline{r})}{4\pi|\overline{r}' - \overline{r}|^3} dV , \tag{5}$$

where V is the volume containing the current $\overline{J}(x,y)$, i.e., the bay water, and $\overline{r}$ is the displacement vector to $\overline{J}(x,y)$. The origin of the coordinate system, from which $\overline{r}$ and $\overline{r}'$ are measured, was set at the midpoint of the feed wire connecting the electrodes. In the actual calculations, Eq. (5) was first expressed as a sum of the contributions from the volumes v_i bounded by the lines connecting the mesh points, in the form

$$\overline{B}(\overline{r}') = \frac{\mu_o}{4\pi} \sum_{\text{all } i} \int_{v_i} \frac{\overline{J}_i \times (\overline{r}' - \overline{r}_i)}{|\overline{r}' - \overline{r}_i|^3} dv_i \; . \tag{6}$$

The integral remaining in Eq. (6) was evaluated by assuming that $\overline{J}(x,y)$ varied linearly over each volume v_i. Thus, representing the values of $\overline{J}$ at the corner of v_i by $\overline{J}_k$, the integral can be evaluated analytically, and we have:

$$\text{integral} = \frac{(\Delta x)^2 d}{4} \sum_{k=1}^{4} \frac{\overline{J}_k \times (\overline{r}' - \overline{r}_i)}{|\overline{r}' - \overline{r}_i|^3} \text{, for square-top } v_i ,$$

or

$$\text{integral} = \frac{(\Delta x)^2 d}{6} \sum_{k=1}^{3} \frac{\overline{J}_k \times (\overline{r}' - \overline{r}_i)}{|\overline{r}' - \overline{r}_i|^3} \text{, for triangle-top } v_i .$$

For the actual calculation of the magnetic field, the depth of the bay was fixed at a uniform 2 m. The electrodes were fed via 180 m of #4 AWG aluminum cable connected to two 12 V automobile batteries in series. The resistance of the feed wire was 0.24 Ω, and the above computations showed that the current path in the water presented a resistance of 0.53 Ω. The resulting current produced a total magnetic field in the ionospheric E region (altitude = 100 km) of 0.017 mγ which, because of the idealizations employed, is subject to an error of approximately ±50%. This field is not large in an absolute sense, but it is a surprisingly large field to be produced by two automobile batteries in series with 180 m of wire, and a small peninsula.

Furthermore, the region of maximum field covers a large area of the E-region: the field is at or above 97% of its maximum value over a circular area of about 10 km radius at 100 km altitude. It falls to about 52% of the maximum at 100 km north or south of the point of maximum field (directly above the peninsula) and to about 34% at 100 km east or west.

To illustrate the great "gain" of the peninsula system, we compare the calculated field (actual field) with the field that would be generated by the same total current flowing through a wire laid along the shoreline of the peninsula from one electrode to the other. We calculate a dipole moment of 1.8×10^6 Am^2 for this current loop, and it would produce a magnetic field of 3.6×10^{-4} mγ at a point 100 km directly above. The field produced by the model peninsula-sea water combination is about 49 times larger than this comparison value, and, assuming a 20% loss of current through the peninsula (as suggested by our magnetic field measurements), the field produced by the actual peninsula-sea water combination is about 35 to 40 times larger than the comparison value. Note that this comparison does not take into account the greater power that would be required to drive the current through the wire outlining the peninsula. For the same power, the gain of the peninsula/sea water system over the peninsula/wire model system is even larger than the factor of 35 to 49 that we have just derived.

V. DISCUSSION AND CONCLUSION

Before we reach a final conclusion concerning the feasibility of the peninsula method for ULF signal generation, there are several possible problems with the method that need to be considered. These problems include the loss of electric current through the peninsula, reduction of the magnetic fields by induced (eddy) currents in the sea floor, and possible detrimental environmental effects.

We have already indicated in this report that it is desirable for most of the current to flow in the sea water around the peninsula, with minimal current flow through or under the peninsula. Clearly, any current that flows through the peninsula directly beneath the electrode feed wires does not contribute to the magnetic moment of the desired horizontal current loop. There are a number of possible methods by which this current flow can be minimized; for example, by the choice of a relatively resistive peninsula, and by suitable design, positioning, and orientation of the electrodes. However, even with careful planning, it will probably be impossible to completely avoid some current flow through or under the peninsula. Thus, it is important for us to point out that this current flow is not necessarily wasted but may, on the contrary, contribute to the ULF wave generation process.

Unless the current flow through the peninsula takes place directly beneath the electrode feed wires, the current will in general both contribute to the magnetic moment of the horizontal current loop and also produce a vertical current loop. The net contribution to the

moment of the horizontal current loop will increase this moment and contribute to the ULF wave generation process. Similarly, the current forming the vertical loop is not necessarily lost, since a vertical current loop can be as effective for the production of Pc 1 pulsations as a horizontal current loop (Greifinger and Greifinger, 1974).

Our assumption of a nonconducting peninsula and sea floor not only has the effect of eliminating current flow through the peninsula, but it also eliminates induced currents in the medium underlying the effective horizontal current loop. These induced currents reduce the magnetic field produced by the current loop and therefore reduce its effectiveness for ULF wave generation. If the materials comprising the sea floor were perfectly conducting, it would be possible to use image techniques to calculate the magnetic fields produced by the induced currents. However, since the materials comprising all realistic sea floors are only imperfect conductors (often with conductivities 50 to 1000 times smaller than the conductivity of sea water), it is necessary to work directly with the complete field expressions for a two or more layered medium. Evaluation of these field expressions is difficult. However, Fraser-Smith and Bubenik (1974) have evaluated the field expressions for the case of a large horizontal current loop lying on a semi-infinite homogeneous medium of conductivity σ, and the results of this work can be used to estimate the effect of a conducting sea floor on the magnetic field produced at ionospheric height by the electric currents flowing around a peninsula.

Fraser-Smith and Bubenik (1974) found that the magnetic field at E region height directly above a horizontal current loop is reduced by

less than 20% for frequencies close to 1 Hz and for σ corresponding to the conductivity at an average continental location (i.e., $\sigma \approx 10^{-4}$ mho/m). For $\sigma = 10^{-3}$ mho/m the reduction would be about 51% and for $\sigma = 10^{-2}$ mho/m the reduction would be 81%. Thus, induced currents in the layer beneath the current loop can substantially reduce the ionospheric magnetic field produced by the current loop if the layer has an effective conductivity greater than about 10^{-4} mho/m.

It is difficult to obtain sea floor conductivities that are relevant to the present discussion of the peninsula method. Kermabon et al. (1969) made measurements of the conductivity of the unconsolidated sediments comprising the top 10 m of the Tyrrhenian abyssal plain west of Naples and obtained values in the range 2 to 3 mho/m (the conductivity of the bottom water was about 4.5 mho/m). At greater depths in the sea floor, as the sediments consolidate, it would be expected that the conductivity would decrease. Kirkpatrick (1977), for example, reports conductivities in the range 10^{-1} to 10^{-2} mho/m at depths of 160 to 400 m for drill holes in the floor of the Atlantic Ocean. The skin depth of a 1 Hz electromagnetic signal in material of conductivity 10^{-1} mho/m is 1.6 km, and in material of conductivity 1 mho/m the skin depth is 503 m. Thus, the ULF electromagnetic fields with which we are concerned can obviously penetrate the comparatively highly conducting upper layers of the sea floor with only small to moderate loss of amplitude. At greater depths, particularly since the sea floor of interest adjoins the shore, the conductivity should become more typical of the crustal materials underlying land areas. The effective sea floor conductivity for the 1 Hz electromagnetic fields under these

conditions is more likely to be typical of the 10^{-4} mho/m value for an average continental location (Fraser-Smith and Bubenik, 1974) than it is of the 10^{-1} to 10^{-2} mho/m value for shallow depths in the sea floor.

Longuet-Higgins (1949) used observations of the potential difference between the ends of telephone cables to deduce a value of 6×10^{-3} mho/m for the mean effective conductivity of the sea bed in the English Channel. By choice of the location of the peninsula in a region where both the peninsula and underlying sea floor consist of rock of low conductivity (such as granite), it should be possible to have an effective sea floor conductivity that is significantly less than the 6×10^{-3} mho/m value for the English Channel, i.e., a conductivity on the order of 10^{-3} mho/m. For this sub-surface conductivity, there is a reduction of about 50% in the magnetic fields produced at E region height at 1 Hz by a horizontal current loop on the surface; and a similar reduction is expected to occur in the peninsula method for the same effective sea floor conductivity. Although this is a substantial reduction, it is more than compensated for by the much greater magnetic fields produced in the ionosphere by the peninsula system for a given input current.

As we have seen, one of the principal advantages of the peninsula "antenna" for ULF wave generation, compared with a wire loop of comparable area, is the very low resistance of the greater part of the current path. Thus it is possible to drive a large current, on the order of 3000 to 5000 A, around the path with a comparatively small voltage difference. For this reason, and because it is desirable

for the peninsula to have a large area (on the order of 100 to 1000 km^2) with a consequent large perimeter, the voltage gradients produced in the sea water surrounding the peninsula are everywhere small except possibly in the immediate vicinity of the electrodes. Lipa et al. (1975), for example, calculated a current density of 0.01 A/m^2 just off the extreme end of their peninsula, which implies a voltage difference of only 0.005 V across the length (assumed to be 2 m) of a swimmer at that location. [Note: the 0.03 V published by Lipa et al. (1975) for this voltage difference across the swimmer is too large by a factor of 6 (B. L. Lipa, personal communication, 1977)].

Similarly, because of the large volume of water involved, the electric current density in the water surrounding the peninsula is everywhere small except possibly in the immediate vicinity of the electrodes. To illustrate, in the particular example considered by Lipa et al. (1975) the current density in the sea is everywhere less than 0.6 A/m^2 (the current density next to the electrodes), and throughout most of the sea the current density is less than 0.01 A/m^2. Adjacent to the electrodes the current density can be reduced to any desired level (within broad limits set by the particular peninsula/sea configuration) by increasing the size of the electrodes. Finally, we note that larger total currents and probably much higher current densities than those proposed for the peninsula method are produced by other systems presently in operation without apparent harmful environmental effects. For example, the Physics Bulletin of July 1977 (p. 239) quotes a maximum total current of 7200 A through sea water for the active cathodic protection system that is to be installed

on and around an offshore platform in the North Sea, and similar active cathodic protection systems are already in use at other locations.

Thus, provided care is taken with the electrode design and shielding is provided, if necessary, there are likely to be no undesirable environmental effects associated with the voltage gradients and current densities in the sea water surrounding the peninsula.

ULF magnetic field fluctuations with amplitudes in the range 100 to 1000 γ will be produced on the peninsula and in its vicinity when ULF wave generation experiments are conducted. Protection of telephone and other conducting line systems would be necessary to prevent arcing and other problems due to induced currents. Fortunately, a large part of the area surrounding the peninsula is occupied by the sea, and the number of conducting line systems that are likely to be affected by the peninsula "antenna" will be reduced accordingly.

Possible biological effects of the magnetic fields produced by the peninsula "antenna" (as well as those produced by other ground-based current loop methods for ULF wave generation) are difficult to assess, since there have been few published studies of the biological effects of magnetic field fluctuations below 10 Hz. We note, however, that ULF geomagnetic field fluctuations with amplitudes in the range 5 to 50 γ can occur during geomagnetic storms at high latitudes and during natural "giant" pulsation events. In addition, modern mass transit systems such as the San Francisco Bay Area Rapid Transit (BART) system can produce large amplitude ULF magnetic field fluctuations on the ground (Fraser-Smith, 1977) and it is probable that the amplitude of these fluctuations can exceed 100 γ

for locations close to the tracks. Thus, although further studies are clearly desirable, it appears likely that the magnetic fields produced on the peninsula and in its vicinity will be harmless to living organisms. Finally, we note that the peninsula "antenna" will not be in continuous use. Infrequent use of the peninsula "antenna" will, of course, minimize the possibility of harmful environmental effects.

The most important similarities and differences between the peninsula method for ULF wave generation in the ionosphere and magnetosphere and the original ground-based current loop method (which requires a large horizontal wire loop) can be summarized as follows:

(1) The ULF wave generation mechanisms for the two methods are identical; the primary requirement being the production of as large a ULF magnetic field as possible in the lower ionosphere.

(2) Fraser-Smith and Bubenik (1974) calculated that for an average continental location the conducting earth would reduce the magnetic field produced by a horizontal wire loop at E region height by less than about 20% for frequencies close to 1 Hz. In this report, we deduce that the potentially higher effective conductivity of the sea floor/peninsula combination may reduce the equivalent field produced by the peninsula method by about 50%. Thus, from this point of view, the horizontal wire loop method is likely to be more efficient than the peninsula method. It should be pointed out, nevertheless, that the two methods would probably have similar efficiencies, insofar as losses produced by the conducting earth are concerned, if the wire loop had the same location as the peninsula.

(3) Calculations indicate that the ULF magnetic field produced at E region height by the peninsula method can be up to 50 times greater

than the field produced by the same total ULF current passing through a wire conforming to the perimeter of the peninsula (it is assumed, in deriving this result, that the sea floor and peninsula are nonconducting). In addition, the power expended to drive the ULF current around the peninsula is likely to be substantially less, by perhaps an order of magnitude or more, than the power expended to drive the same ULF current through the wire loop. Thus the ULF magnetic field generated per unit of input power is much greater for the peninsula method than it is for the horizontal wire loop method. This result holds even when the possible differences in effective earth conductivity are taken into account.

(4) Because only a comparatively small amount of electrical wiring is required for the electrode feed wires, the cost of constructing a peninsula "antenna" is likely to be much smaller than the cost of constructing a horizontal wire loop. In addition, the cost of the power system required for the peninsula "antenna," as well as its running costs, will probably be less than the equivalent costs for the horizontal wire loop.

A rough estimate of the cost of a peninsula "antenna" can be obtained by reference to the earlier estimates obtained by Fraser-Smith et al. (1972) for the cost of a horizontal wire loop system: this cost varied from about \$1 million for a single-turn loop of 10 km radius to about \$12 million for a three-turn loop of 50 km radius. These costs should now be increased by perhaps 25% to allow for the decline in purchasing power of the dollar in the interval 1972 to 1977. The principal contribution to these estimated costs was the expense

of the wire loop and its supports. (The wire loop is assumed to be raised off the ground on supports in order to provide maximum heat dissipation. Supports may also be required for the electrode feed wires in the peninsula method.) In addition, even though heavy gauge wire is to be used, the resistances of the two loops are relatively high (2 Ω and 28 Ω) compared with the resistances of possible sea water loops, and the expense of the power systems required to drive currents in the range 1000 to 3000 A through the loop adds substantially to the estimated costs.

In the peninsula method, the principal expense is for the power system. Fraser-Smith et al. (1972) used a cost figure of $50/kW for a dc converter stage, with two converters needed in the one power system. Including the effects of inflation, we adopt $62.5/kW as our new cost figure, and we estimate that the dc converter stage required for a 2.5 MW peninsula power system would cost about $320,000. This system should be capable of driving a 3000 A ULF square wave current around a peninsula of area equivalent to that of a 50 km radius loop, and doing so continuously for many hours or days, if required. If continuous operation is not required, as may be the case for an initial full-scale ULF generation experiment, much simpler power systems could be used. For example, a power system using ordinary automobile batteries could probably be constructed for less than $100,000. Assuming the neck of the peninsula is on the order of 1 km or less in width, it is unlikely that the cost of the electrodes and their feed wires would approach the estimated cost of $360,000 obtained by Fraser-Smith et al. (1972) for the wire and its supports for the 10 km radius loop. We estimate

a maximum of roughly $150,000 for the cost of the peninsula electrodes and their feed wires. Allowing for additional labor and contingencies, we estimate the cost of a peninsula antenna to be approximately in the range $250,000 to $500,000. This cost estimate should be compared with the approximately $15 million (in 1977 dollars) estimated by Fraser-Smith et al. (1972) for the three-turn 50 km radius horizontal loop, which would have about the same ULF hydromagnetic wave generating capability as the peninsula "antenna." These cost estimates are necessarily approximate, and they do not cover site-related contingencies such as the need to purchase land or to substantially extend a standard 60-70 kV power transmission line. Nevertheless, it is clear that the peninsula method, while having the same ULF wave generation capability as a large horizontal wire loop, will cost well over an order of magnitude less to implement.

In conclusion, the experimental and theoretical results we have obtained during this study indicate that the peninsula method for ULF wave generation in the ionosphere and magnetosphere is not only feasible, but it is likely to have several substantial advantages over a large horizontal wire loop used for ULF wave generation. These probable advantages for the peninsula method include lower construction and running costs and the production of much greater ULF magnetic field amplitudes in the lower ionosphere per unit of input power. Because the two methods of ULF wave generation are otherwise equivalent, further experiments on the peninsula method and, in particular, a full-scale ULF wave generation experiment using the peninsula method, appear to be desirable.

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